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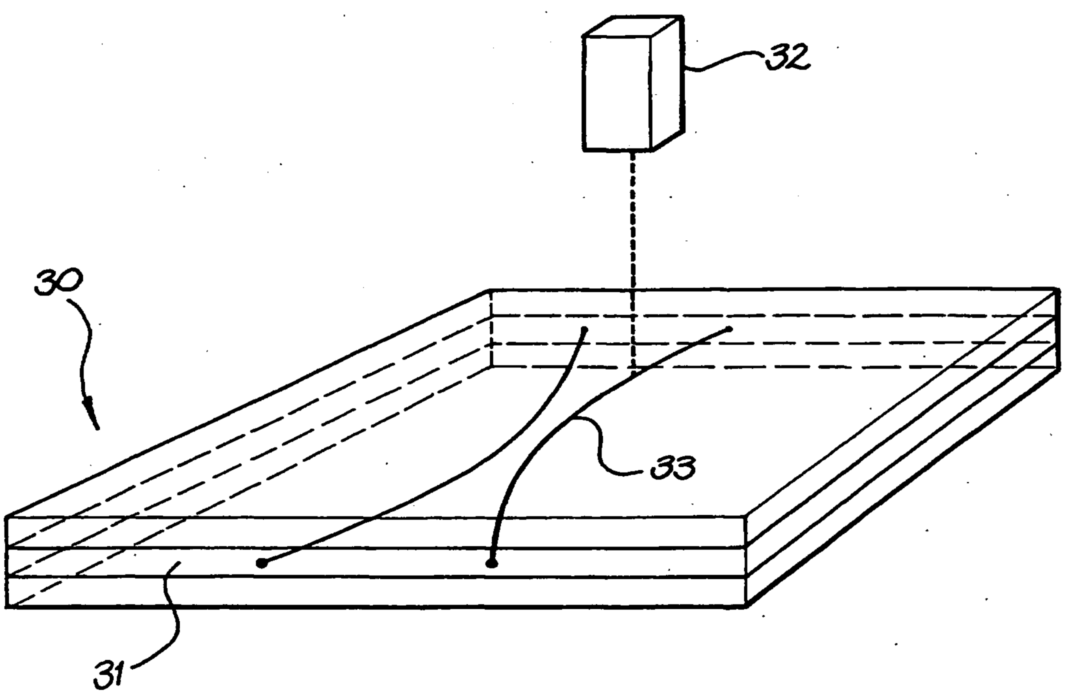
(54) Title: METHOD OF FORMING AN OPTICAL WAVEGUIDE DEVICE



(57) Abstract: A method of forming an optical waveguide device in a photosensitive material, the method comprising scanning a laser beam across the material to induce refractive index changes in the material to form at least one waveguide of the device, wherein the scanning speed is varied to create a refractive index taper in the waveguide of a selected functional form.

WO 00/79320 A1

Method of Forming an Optical Waveguide Device

Field of the Invention

The present invention relates to the field of formation of optical waveguide devices utilizing laser processing including e.g. the formation of digital directional couplers.

Background of the Invention

As telecommunications operators rapidly expand their existing fibre optic networks driven by the ever increasing demand for bandwidth, optical space switching is becoming an important function in all-optical networks. In particular, the adoption of optical space switches enables network reconfiguration and restoration (fault protection) at the optical level, rather than converting the optical signals to electronic form for switching purposes. The architecture of choice for switching devices is the planar lightwave circuit (PLC) since it allows many switching elements to be concatenated logically together to form a switching matrix on a single compact optical "chip".

As shown in Fig. 1, the basis of most PLC's is a trilayer of optically transparent thin films deposited on a substrate of generally silicon or silica 1. The central, or core layer 2 of the sandwich structure normally has higher refractive index than the outer cladding layers 3,4, and this simple system is known as a planar waveguide. Light injected into the core layer 2 undergoes total internal reflection at both core/cladding boundaries and is confined in this transverse dimension, resulting in 1-dimensional light guidance. However as a consequence of the constant refractive index in the plane of the film total internal reflection is not possible, and light spreads or diffracts laterally in the guiding layer. To impart useful functionality to a planar waveguide, 2-dimensional light guidance is required, and planar diffraction must be overcome by locally increasing the refractive index in the core layer. The light guides so formed are known as channel waveguides, the basic elements of optical space switches.

One of the simplest forms of optical space switch is the directional coupler which is illustrated schematically in Fig. 2. In this four port device 10, two identical single mode channel waveguides 11,12 are brought into close proximity with one another such that the electric field of one guided mode overlaps with the high refractive index guiding region of the other waveguide. With light injected into port 1, a resonant interaction results in an oscillatory power transfer between the two waveguides with device length. This occurs since the guides are identical and the lightwaves in the individual waveguides propagate through the structure at the same velocity. Under these conditions the guides are said to be phase matched and 100% power may be transferred between guides. Judicious choice of the length of the interaction region allows any fraction of optical power to be split between the output waveguides, ports 3 and 4. For switching applications, the interaction length is often chosen such that all the power entering port 1 exits at port 3; the device is said to be in the 'cross' state.

Switching can then be achieved by modifying the refractive index of one or both of the waveguide core regions such that propagation of light waves through the individual guides of the structure occurs at different velocities. The waveguides are then phase mismatched, the interaction between the guides is no longer resonant and the power transfer effect is diminished such that light injected into port 1 now exits through port 4. The device is then said to be in the "bar" state. In practice, detuning of the device may be achieved by the thermo-optic effect (polymer, sol-gel and silica PLC's), the electro-optic effect (ferroelectric waveguides) or carrier injection (semiconductor waveguides). For low speed (~1msec) switching applications the thermo-optic mechanism is more favorable since the effect is independent of polarization, allowing all input light polarization states to be switched by the same amount. A typical switching response of a directional coupler operating under this

regime is shown in Fig. 3, where the crosstalk, X, is defined as;

$$X = 10Log_{10}\left(\frac{P_3}{P_3 + P_4}\right) \qquad (1)$$

and P_i is the optical power at port i.

It can be seen that the switching process is efficient but sidelobes in the device response are always present. To maintain a low crosstalk value in the switched state therefore requires that operation occur in a narrow region e.g. 20 between sidelobes, placing severe constraints on the associated control system electronics. A reduction in sidelobe level can be obtained through the use of distributed coupling, in which instead of the two waveguides running parallel to one another, their separation is tapered in a specific continuous manner reaching a minimum at the centre of the device. This procedure can minimize sidelobe level but still requires operation in a sidelobe minimum to achieve sufficiently low crosstalk. A digital switching response exhibiting no sidelobes would therefore be advantageous.

An alternative but equivalent view of the coupling process is obtained by considering the compound two-waveguide structure. In this model coupling is described by the interference of the normal modes of the compound structure which maintain their shape along the device length but travel at different velocities. A cross state is obtained when the device length is such that the supermodes have a relative phase difference of π or odd multiples thereof, interfering constructively at port 3 and destructively at port 4. The presence of sidelobes in the switching response may then be attributed to further interference effects as the device is detuned.

The major disadvantage of directional couplers for optical switching applications is that although very low crosstalk values (<-40dB) are theoretically possible, to achieve this performance in a real world device requires

that a supermode phase difference of π must be accurately and repeatably attained for the unswitched state. Small fluctuations in the core refractive index or device length accrued in the manufacturing process, and the additional requirement of diverging the waveguides to a 250μm separation to interface with optical fibres, currently renders -40dB crosstalk values in this class of switching device an elusive goal. In addition, the emergence of wavelength division multiplexing (WDM) as the accepted method of expanding the bandwidth of existing optical networks introduces the requirement that the response of optical space switches be independent of wavelength over a range of typically 40nm. Clearly since directional couplers operate through wavelength dependent interference effects, the low crosstalk criterion cannot be met for all wavelengths simultaneously and this class of device is unsuitable for these applications. Alternative device structures exhibiting wavelength independent, digital switching responses and low crosstalk are therefore sought.

A digital directional coupler (DDC) device that potentially satisfies the above requirements has been proposed and analyzed theoretically, (R. R. A. Syms and R. G. Peall, 'The digital optical switch: analogous directional coupler devices', *Optics Communications*, Vol. 69, No. 3,4, pp. 235-238, 1989, R. R. A. Syms, 'The digital directional coupler: improved design', *IEEE Photonics Technology Letters*, Vol. 4, No. 10, pp. 1135-1138, 1992. A schematic of the device is shown in Fig. 4a. This four port device comprises a distributed coupling directional coupler in which each waveguide is tapered in effective index, N_{et}, in opposite directions, with a graph of the tapering being illustrated in Fig. 4b. The effective index will be proportional to waveguide width and/or core refractive index. In the unswitched state, the waveguides are identical and therefore phase matched in the centre of the device where their separation is a minimum and the interaction or coupling strength, $\kappa(0)$, is maximized. Significant power transfer between the waveguides therefore

takes place in this region to produce a device in the cross state. Detuning the device in a similar manner to standard directional coupler switches moves the phase matching position away from the device centre to regions of increased waveguide separation and consequently reduced coupling strength, $\kappa(z)$. Power transfer is therefore inhibited and the device is placed in the switched bar state. The key difference between this type of optical switch and a standard directional coupler is that operation is based on the 'slow changing of shape' or adiabatic evolution of a single 'supermode', induced by the gradual effective index changes along the device. Since only one 'supermode' is excited in the compound system, interference effects do not occur and the device shows the required properties of wavelength independent, digital switching. To maintain power in only one 'supermode' along the device and achieve adiabatic operation requires that the difference in effective indices of the two 'supermodes', ΔN_{ef}, supported by the compound system be maximized throughout the interaction length. Under this condition a difference in shape between 'supermodes' is maintained and the following constraints on device design may be derived;

$$\kappa(z) = \kappa(0)\sin\theta \qquad (2)$$

$$\Delta N_{ef} = \left(\frac{\lambda}{2\pi}\right)\kappa(0)\cos\theta \qquad (3)$$

where λ is the wavelength of light and θ is an S-shaped rotation function of typical form;

$$\theta = \left(\frac{\pi z}{L}\right) - 0.5\sin\left(\frac{2\pi z}{L}\right) \qquad (4)$$

for an interaction length, L. From equation (3) it is therefore clear that adiabatic operation will be best

obtained with strongly coupled waveguides (large $\kappa(0)$), requiring a small central waveguide separation.

Summary of the Invention

In accordance with a first aspect of the present invention, there is provided a meth a method of forming an optical waveguide device in a photosensitive material, the method comprising scanning a laser beam across the material to induce refractive index changes in the material to form at least one waveguide of the device, wherein the scanning speed is varied to create a refractive index taper in the waveguide of a selected functional form.

The laser beam preferably can include a doughnut type irradiance distribution such as a TEM_{01}* mode laser beam.

In one embodiment, the optical waveguide device comprises a digital directional coupler, and the method comprises scanning the laser beam across the material to induce refractive index changes in the material to form at least two waveguides of the coupler.

The laser can be utilized to produce a series of refractive index tapers in the waveguide of specified functional form. In one example, the mode of the laser can be chosen so as to provide an increased coupling strength of evanescently coupled waveguide devices constructed in accordance with the method. The method can be further utilised to reduce the optical cross coupling between connecting waveguides in an optical switching matrix. The method can also be utilised to form multiple optical switches on a single planar wafer. The method can also be utilised to produce substantially continuous refractive index taper profiles in laser written channel waveguides.

In accordance with a second aspect of the present invention, there is provided an optical waveguide device when produced utilising the method of the first aspect of the present invention.

Brief Description of the Drawings

Notwithstanding any other forms which may fall within the scope of the present invention, preferred forms of the

invention will now be described by way of example only, with reference to the accompanying drawings in which:

Fig. 1 illustrates a sectional schematic view of a planar waveguide;

Fig. 2 illustrates a schematic of a channel waveguide directional coupler;

Fig. 3 illustrates a graph of the typical response of a directional coupler;

Fig. 4a illustrates a schematic of a typical digital directional coupler;

Fig. 4b illustrates the effective index for the arrangement of Fig. 4a;

Fig. 5 illustrates an example effective index and maximum core refractive index of a TEM_{01}* written waveguide, as a function of writing velocity;

Fig. 6 illustrates a comparison of coupling strengths for a TEM_{01}* and TEM_{00} laser beam; and

Fig. 7 illustrates a simple schematic of the writing process of the preferred embodiment.

<u>Description of Preferred and Other Embodiments</u>

In practical terms, the fabrication of optical waveguide devices such as digital directional couplers is problematic using standard processes. In the microelectronics industry, the construction of complex waveguide structures normally utilizes a standard patterning technique known as mask photolithography. The first step in this process is to deposit an additional thin film of photoresist onto the planar waveguide core, usually by spin coating. The photoresist film is then preferentially exposed to a broadband extended UV source through an amplitude mask such that a photochemical reaction is initiated below the high transmission areas of the mask and the mask pattern (or its inverse) transferred to the photoresist layer. The pattern may then be defined in the waveguide core layer by removing core material from the unwanted regions by a process such as reactive ion etching (RIE). Removal of the remaining resist and

overcladding with a low refractive index film completes the standard processing of the PLC.

In the preferred embodiment, a more direct approach may be taken utilizing materials such as plastics, ormosils and some glasses that allow refractive index patterning to be achieved without the use of an additional photoresist layer. In this class of materials, direct exposure generally to UV radiation initiates a photochemical reaction that raises the refractive index of the core material, enabling channel waveguides to be formed. The materials are generically described as photosensitive, and, as will be demonstrated, enable DDC devices to be accurately defined using a new fabrication method.

The requirement for strongly coupled waveguides in digital directional couplers means that fabrication methods involving material removal such as RIE are not ideal as it is difficult to define individual waveguides in the central region of the structure with sufficient accuracy. In addition, since an extended UV source is used in both these photolithographic techniques the exposure is uniform across the whole wafer, and hence an induced refractive index change cannot vary from one part of the waveguide structure to the next. Tapers in guide effective index must therefore be obtained through tapers in waveguide width which places severe tolerances on the production of a suitable mask. Photolithographic masks are usually produced by electron beam writing systems which approximate continuously varying structures with constant segments offset by a step size of typically 50-100nm. Although small, these 'hard', discontinuous steps impact detrimentally on the minimum crosstalk value that can be obtained in waveguide devices. In addition, since the total change in guide width required to obtain a suitable change in effective index is small ($\leq 1\mu m$) in comparison with the interaction length (10-20mm), accurate control over the rotation function, θ, is not possible. To date mask-based photolithographic methods combined with RIE have

not produced mode evolution coupler type devices with acceptable optical performance.

In the preferred embodiment, an alternative fabrication process is used in which refractive index tapers are the primary method for producing the device. Importantly this method utilises a laser direct writing (LDW) technique. In contrast to standard mask photolithography, in the LDW process a photosensitive planar waveguiding film is accurately traversed under a focused laser beam to locally increase the refractive index and directly delineate the channel waveguides without the use of a mask. For constant laser power, the exposure and therefore the refractive index of the photosensitive material is typically related to the writing velocity. For example, Fig. 5 illustrates, for an example photosensitive material, the effective index and maximum core refractive index of a written waveguide as a function of writing velocity. Clearly by controlling the writing velocity, the refractive index of the waveguide core and therefore the waveguide effective index can be continuously varied along the device length. Furthermore, since the generated pattern is under direct software control, rotation functions of complex mathematical form may be experimentally produced. In comparison with mask technologies, although segmentation is still present, the use of spline tracking curves in both position and velocity results in 'soft' steps which do not affect crosstalk to a large degree, enabling values of <-40dB to be achieved. Therefore, the refractive index tapering achieved via LDW becomes a practical way of implementing mode evolution type device design.

It has been found that as a result of the scanning process using a laser writing with a Gaussian (TEM_{00}) laser beam the waveguide produced has a laterally graded refractive index profile. The use of a 'doughnut' (TEM_{01}*) laser beam produces waveguides with a more step-like refractive index distribution. Fig. 6 illustrates a comparison of the coupling strengths for the two different

type of laser beams. It can be seen that the TEM_{01}* laser beam produces a larger value (typically by a factor of 1.6) of coupling strength, $\kappa(0)$, for the same waveguide separation and maximum exposure. With reference to equation (3) this is clearly beneficial for DDC devices.

Fig. 7 provides a simplified schematic view of the processing arrangement of the preferred embodiment in that a wafer 30 having a photosensitive core layer 31 is processed utilising a UV laser 32 utilizing a spatial translation system (not shown) under software control with a particular velocity and displacement profile so as to trace out a requisite path e.g. 33 in the photosensitive layer 31 so as to modify the refractive index in this traced out path.

In general for optical space switching applications, 2x2 switches are insufficient and multiport *NxN* devices are highly desired. It is usual to achieve this through waveguide connection of single 2x2 switching elements into a logical matrix, such that light input at any port can be redirected to any other unused output port independent of (strictly nonblocking) or dependent upon (blocking or re-arrangable nonblocking) the routing connection used. Since the interface to single mode optical fibres need only take place at the input and output waveguides, the requirement to separate the channel waveguides to a 250µm pitch only occurs in these areas of the optical 'chip'. Within the switching matrix itself the connecting waveguides need only be sufficiently separated to inhibit any cross coupling between nearest neighbour guides. In this respect laser written mode evolution type switches also offer advantages over existing methods. For instance, in a switching array constructed from 2x2 directional coupler switching nodes and mask type processing, the connecting waveguides must be the same width to efficiently interface with the input/output waveguides of the directional coupler. The connecting waveguides are therefore phase matched, and the switch matrix design is limited by the need to separate the waveguides to minimize resonant optical power transfer

between them. In the laser direct written DDC case the base device is inherently asymmetric and therefore the input/output waveguides are automatically phase mismatched. Power transfer between connecting waveguides is therefore suppressed independent of their spacing allowing more freedom in the design of the matrix. In particular, the density of connection waveguides per unit area of optical chip may be increased, reducing the overall dimensions of optical space switch matrices.

It would be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiment without departing from the spirit or scope of the invention as broadly described. The present embodiment is, therefore, to be considered in all respects to be illustrative and not restrictive.

<u>We Claim</u>:

1. A method of forming an optical waveguide device in a photosensitive material, the method comprising scanning a laser beam across the material to induce refractive index changes in the material to form at least one waveguide of the device,

wherein the scanning speed is varied to create a refractive index taper in the waveguide of a selected functional form.

2. A method as claimed in claim 1 wherein the laser beam has a doughnut type irradiance distribution.

3. A method as claimed in claims 1 or 2, wherein the optical waveguide device comprises a digital directional coupler, and wherein the method comprises the steps of scanning the laser beam across the material to induce refractive index changes in the material to form at least two waveguides of the coupler.

4. A method as claimed in any previous claim wherein the laser is a TEM_{01}* mode laser.

5. A method as claimed in any previous claim wherein the mode of the laser is chosen so as to provide an increased coupling strength between adjacent ones of the waveguides.

6. A method as claimed in any previous claim wherein the photosensitive material is in a planar form.

7. A method as claimed in any one of claims 3 to 6 wherein the scanning speed is varied during the forming of each waveguide in a manner such that adjacent ones of the waveguides are refractive index tapered in opposite directions.

8. An optical waveguide device when produced utilizing the method of any previous claims.

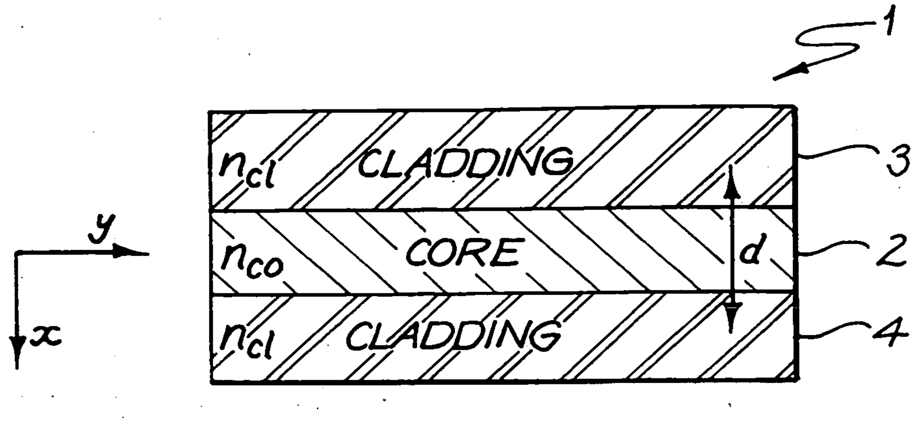

1
n_{cl} CLADDING
3
y
n_{co} CORE
d
2
x
n_{cl} CLADDING
4

FIG. 1

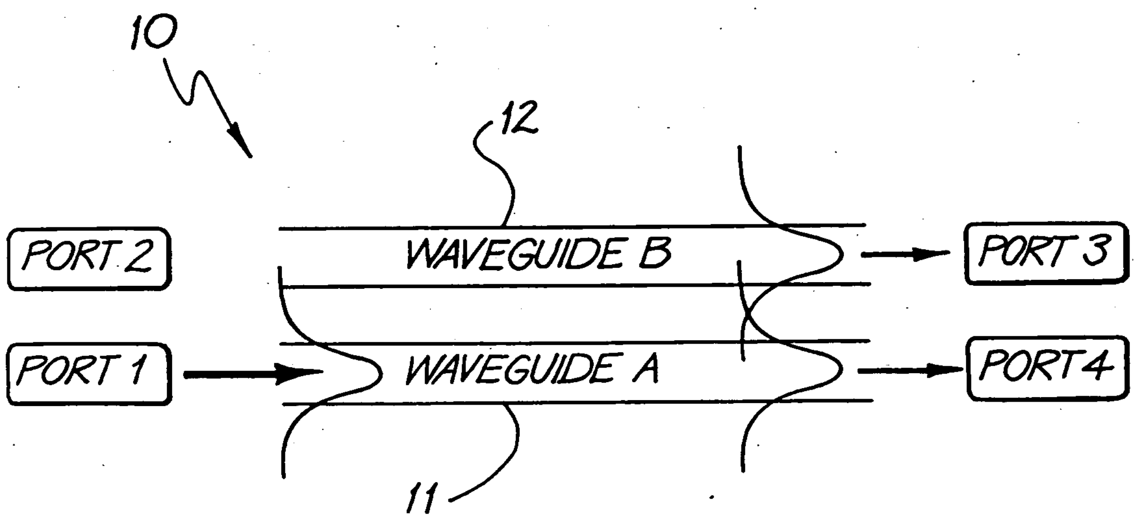
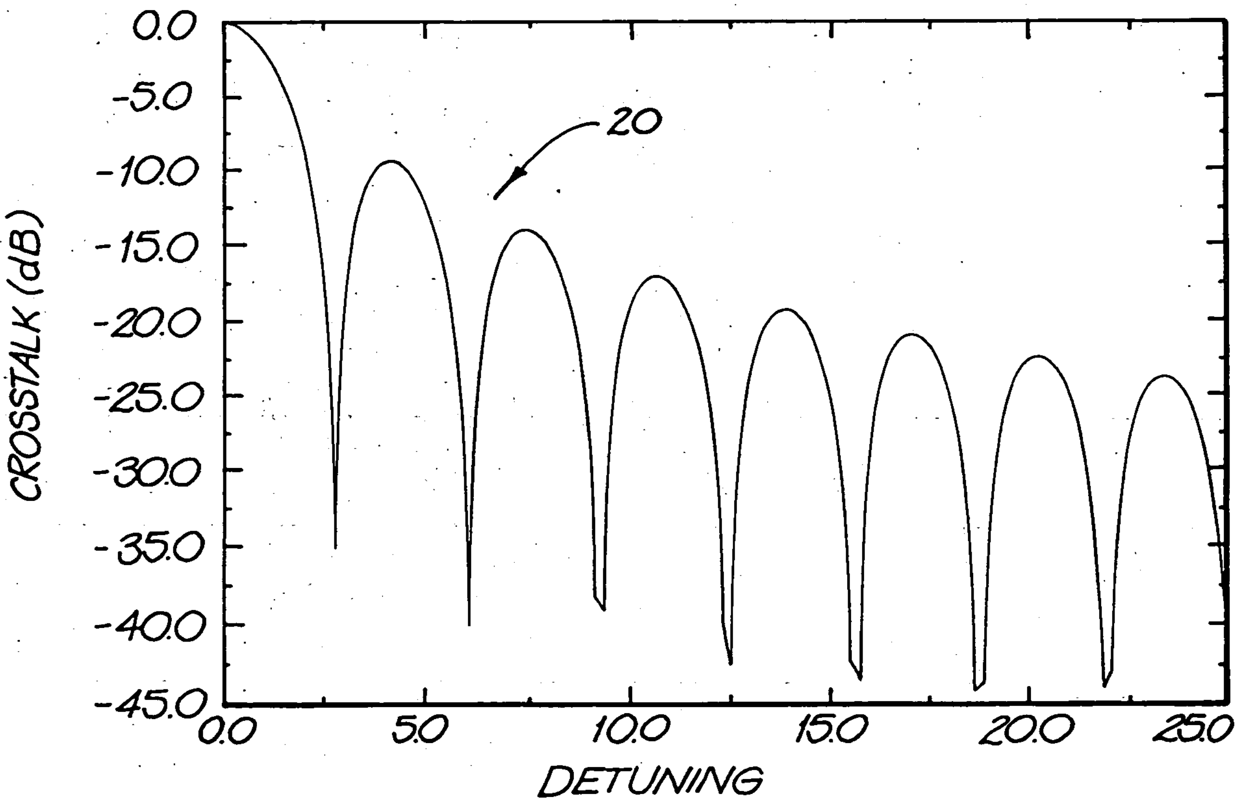

10
12
PORT 2
WAVEGUIDE B
PORT 3
PORT 1
WAVEGUIDE A
PORT4
11

FIG. 2



0.0
-5.0
-10.0
-15.0
-20.0
-25.0
-30.0
-35.0
-40.0
-45.0
CROSSTALK (dB)
20
0.0
5.0
10.0
15.0
20.0
25.0
DETUNING

FIG. 3

SCHEMATIC & EFFECTIVE INDEX TAPERS OF A TYPICAL DIGITAL DIRECTIONAL COUPLER IN THE CROSS (SOLID) & BAR (DASHED) STATES.

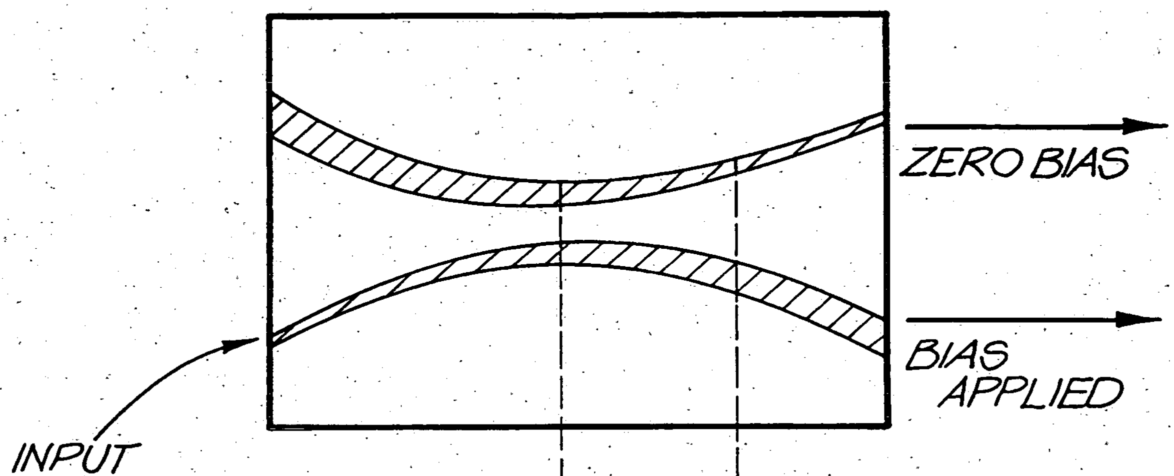


FIG. 4a

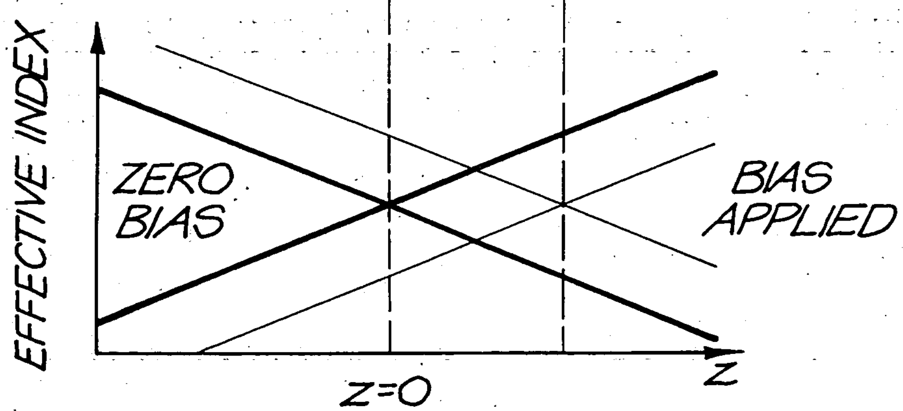


FIG. 4b

EFFECTIVE INDEX (SOLID) & MAXIMUM CORE REFRACTIVE INDEX (DASHED) OF A $TEM_{01}{}^*$ LASER WRITTEN WAVEGUIDE AS A FUNCTION OF WRITING VELOCITY.

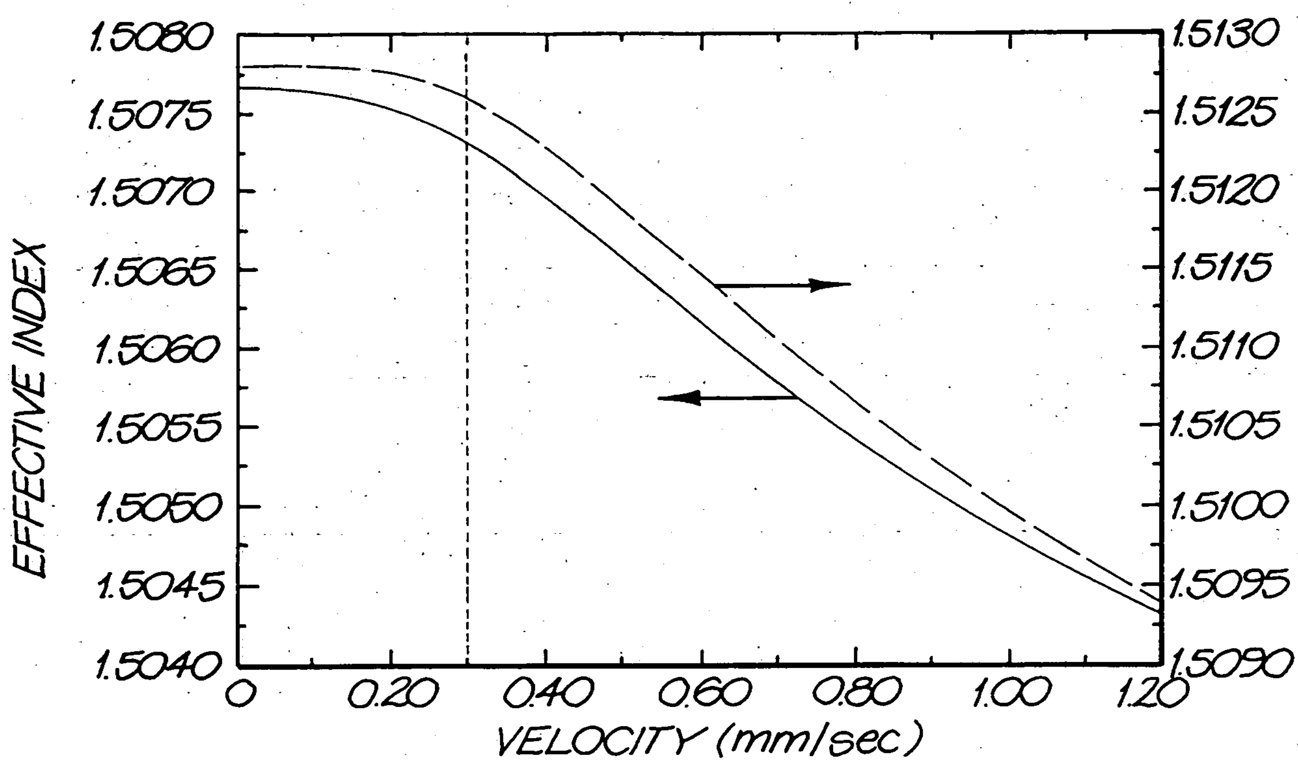


FIG. 5

COMPARISON OF COUPLING STRENGTHS, κ(O), FOR TEM$_{01}$* (SOLID) & TEM$_{00}$ (DASHED) LASER WRITTEN DIRECTIONAL COUPLERS WITH EQUAL WAVEGUIDE SEPARATION & EXPOSURE.

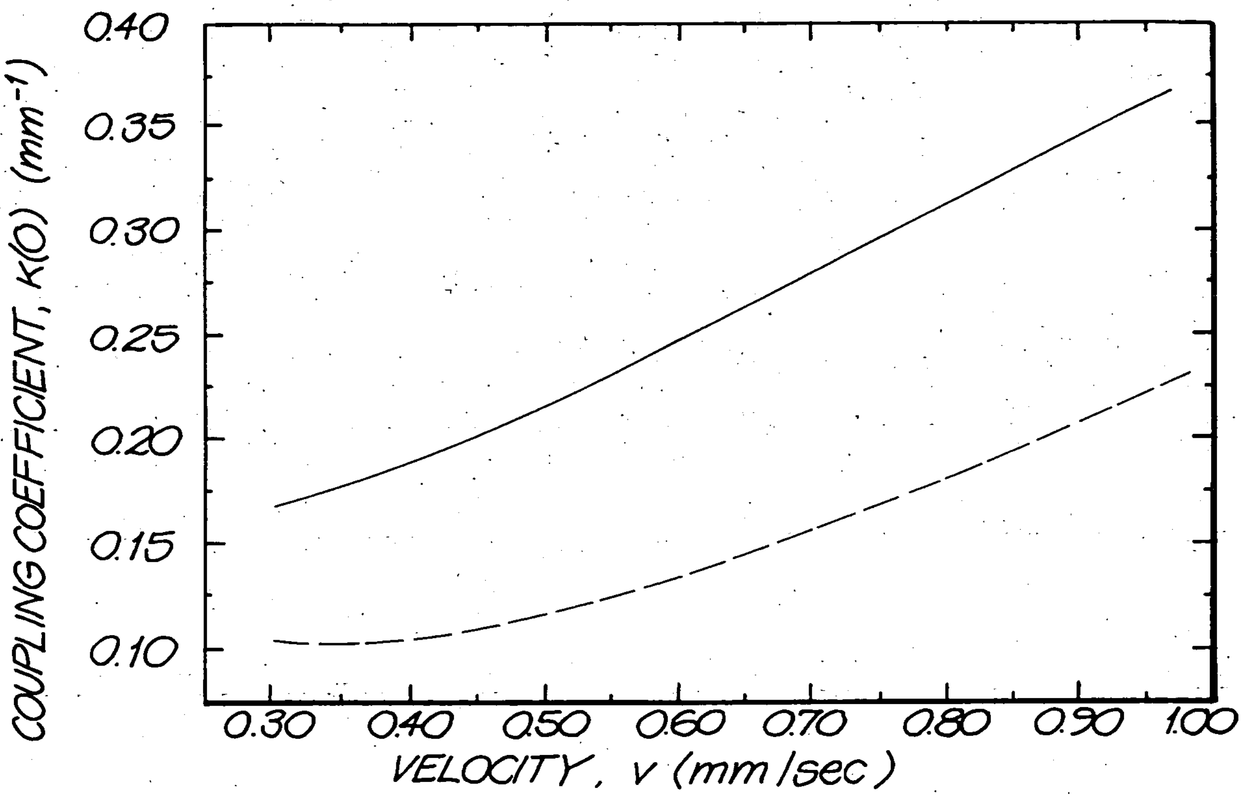


FIG. 6

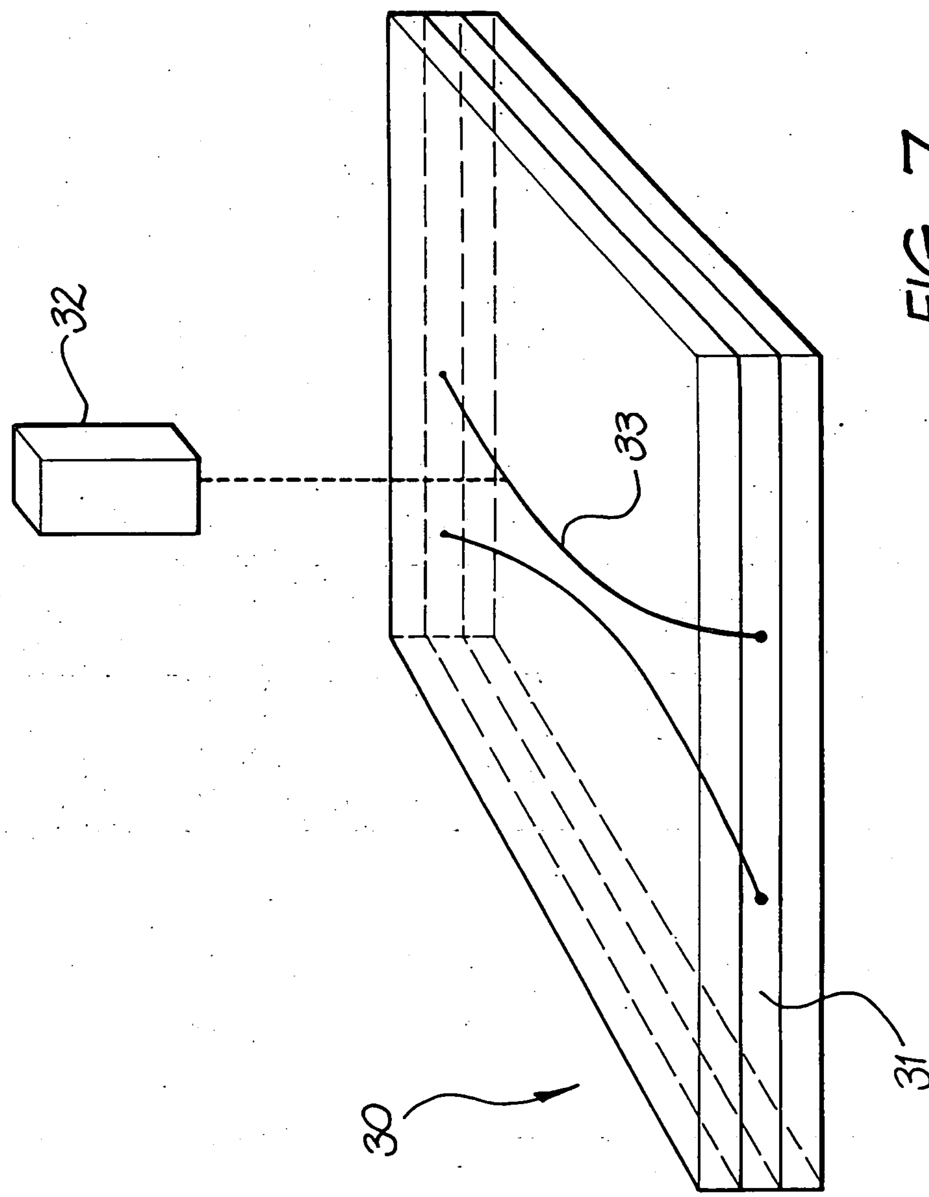


FIG. 7

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU00/00698

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl. 7: G02B 6/26, 6/35

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC G02B 6/-

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
DWPI, JAPIO

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	US 4886538 A (MAHAPATRA) 12 December 1989 whole document particularly col 3 line 31 - col 4 line 29, figures 1 & 2 and col 5 lines 9-14	1, 3, 5-6, 8 1-6, 8
Y*	ACOFT'98 Proceedings: 23rd Australian Conference on Optical Fibre Technology (5-8 July 1998, Melbourne, published pp 37-40), Charters R *et al* "Laser Direct Writing of Polymeric PLC's using a TEM01* Beam" see whole document	1-6, 8
Y*	US 5402511 A (MALONE et al) 28 March 1995 whole document (*to be combined with the first citation)	3, 6, 8

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"&" document member of the same patent family

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17 July 2000	24 JUL 2000

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INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
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US	4886538	CA	1323194	EP	302043	JP	1049004
US	5402511	NONE					

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